On a Formation Scenario of Star Clusters

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Abstract. Most formation scenarios of globular clusters assume a molecular cloud as the progenitor of the stellar system. However, it is still unclear, how this cloud is transformed into a star cluster, i.e. how the destructive processes related to gas removal or low star formation efficiency can be avoided. Here a scheme of supernova (SN) induced cluster formation is studied. According to this scenario an expanding SN shell accumulates the mass of the cloud. This is accompanied by fragmentation resulting in star formation in the shell. Provided the stellar shell expands sufficiently slow, its self-gravity stops the expansion and the shell recollapses, by this forming a stellar system.

I present N-body simulations of collapsing shells which move in a galactic potential on circular and elliptic orbits. It is shown that typical shells (10^5 $M_\odot$, 30 pc) evolve to twin clusters over a large range of galactocentric distances. Outside this range single stellar systems are formed, whereas at small galactocentric distances the shells are tidally disrupted. In that case many small fragments formed during the collapse survive as single bound entities. About 1/3 of the twin cluster systems formed on circular orbits merge within 400 Myr. On elliptic orbits the merger rate reduces to less than 4%. Thus, there could be a significant number of twin clusters even in our Galaxy, which, however, might be undetected as twins due to a large phase shift on their common orbit.

Keywords: globular cluster, stellar dynamics

1. Introduction

The exact formation process of globular clusters is still under debate. Suggested mechanisms include – among other scenarios – e.g. the collapse of giant molecular clouds (GMC) or the collision of molecular clouds (e.g. Fall & Rees (1985), Murray & Lin (1990), Fujimoto & Kumai (1997)). A common feature of most scenarios is the assumption of smooth initial gas distributions which are transformed into the cluster. However, this assumption requires short formation timescales and unusually high star formation efficiencies in order to end up with a gravitationally bound system. An alternative model introduced by Brown et al. (1991) can overcome these difficulties: their scenario starts with an OB-association exploding near the center of a molecular cloud. The expanding shell sweeps up the cloud material and in a later stage the expansion is decelerated and stopped by the accumulated mass as well

as the external pressure of the ambient interstellar medium. The shell itself is assumed to undergo fragmentation and, finally, star formation. If these stars form a gravitationally bound system, this stellar shell will recollapse, by this creating a star cluster.

At the moment a discrimination between different scenarios by direct simulations (starting from first principles) is far out of reach. However, one can study different evolutionary stages in some detail. E.g. Theis (2000) compared in a series of N-body simulations the collapse of thin stellar shells and homogeneous spheres in a galactic tidal field. These calculations were performed for circular and eccentric orbits, but with a constant apogalacticon of 5 kpc. It was found that collapsing shells preferably end in multiple systems, mainly twins, whereas homogeneous spheres either form single clusters or become completely disrupted.

In this paper the influence of the galactocentric distance, i.e. the strength of the tidal field, on the collapse of stellar shells is investigated. Special forcus is put to the survival probability of the formed multiple stellar cluster systems.

2. Numerical Models

The numerical models here start with a thin, spherical shell of 10^5 $M_\odot$, an outer radius of 30 pc and a thickness of 3 pc. The shell is initially at rest, i.e. there is no overall expansion or contraction of the shell with respect to its center. The potential of the Galaxy is modelled by an isothermal halo with a circular speed of 220 $\mathrm{km\,s^{-1}}$. The investigated orbits correspond either to circular orbits or to an elliptic orbit with an apo- to perigalacticon ratio of 10:1. The calculations are performed with $N = 10^4$ particles using a GRAPE3 board.

Circular Orbits. Fig. 1 shows snapshots for collapsing shells on circular orbits. The model starting at 5 kpc is typical for the models resulting in a twin system. With its tidal radius of about 42 pc it is stable against tidal disruption. However, the tidal field is strong enough to delay the collapse along the direction to the galactic center. By this, clumps form at the tips of this line ending up finally in the two clusters. At larger galactocentric distances the mass ratio of both clusters increases: e.g. at 10 kpc two clusters are formed after 20 Myr which have a mass ratio of 5:2. The clusters formed here survive until the end of the simulation at 400 Myr. 20% of the stars initially residing in the shell became unbound. Beyond 11 kpc no twins, but single clusters are formed.

At 3.5 kpc the tidal radius is close to the initial radius of the shell. However, the enhanced tidal field does not result in a disrupted system,

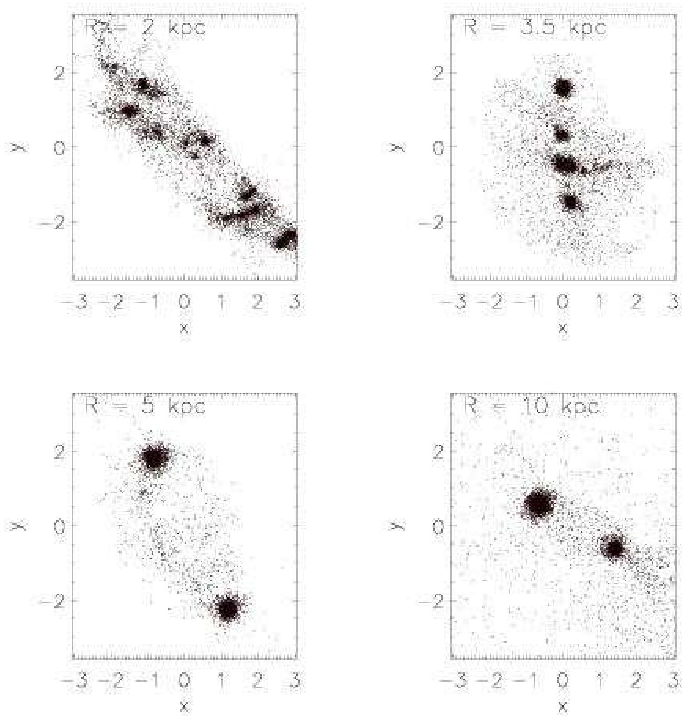

Figure 1. Snapshots at $t = 4 \approx 30$ Myr for circular orbits at different galactocentric distances: $R = 2$ kpc (upper left), $R = 3.5$ kpc (upper right), $R = 5$ kpc (lower left), $R = 10$ kpc (lower right). The spatial unit is 30 pc.

but in a less massive triple system accompanied by several smaller clusters. The triple system dissolves quickly due to merging of two clusters. By this, almost all stars of one cluster became unbound and a twin cluster system is left.

At about 2 kpc the tidal field prevents any collapse in the direction to the galactic center. The fragments usually formed during the collapse of a shell are then not destroyed in a violent collapse, but they survive as gravitationally bound low-mass objects. E.g. 31 clumps exist after $t = 4$ and 12 of them survive the next 400 Myr. At the end of the simulation 76% of the stars are not bound to any cluster.

Survival Rates. The simulations demonstrate that twin formation is expected over a large radial range. On a longer timescale some twins are destroyed by merging, e.g. for circular orbits about 1/3 of the twins merge within 400 Myr. The surviving twins are characterized by large spatial separations which makes them less likely to undergo a subsequent merger. Considering more realistic eccentric orbits, the merger rate drops strongly: less than 4% of the twins (i.e. one system!) under-

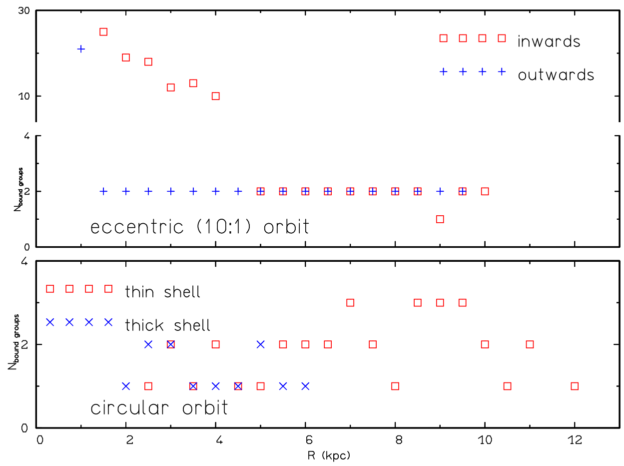

Figure 2. Number of gravitationally bound clusters vs. initial galactocentric distance. Shown are results for t = 400 Myr (end of simulation) for circular (lower panel) and eccentric orbits (upper panel). The "thick shell" denotes simulations with an initial shell thickness of 15 pc. The other simulations are performed with a shell thickness of 3 pc. "Inwards" and "outwards" corresponds to the initial phase on the eccentric orbit.

goes a merger. On the other hand, the fraction of disrupted systems increases to 20%, because shells starting closer to perigalacticon can reach the "disruptive zone" in case of an eccentric orbit. However, the survival probability for formed twins is not affected by this destruction. Therefore, twin globulars might exist even in the Milky Way, but they could be unidentified as twins due to their large separation. Their characteristics (e.g. common orbit, identical metallicity), however, might be used for an observational test of this cluster formation scenario.

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